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Economics of electricity and heat production by gasification or flash pyrolysis of short rotation coppice in Flanders (Belgium)

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ABSTRACT

Short rotation coppice (SRC) seems attractive as an energy crop on degraded land. Gasification and flash pyrolysis are promising technologies for the conversion of SRC into energy or chemicals. A model has been developed to calculate the net present value (*NPV*) of the cash flows generated by an investment in gasification or flash pyrolysis of SRC for the production of electricity or for combined heat and power production. The *NPV* has been calculated and compared for (combined heat and) power stations with an electrical capacity (P_e) between 5 MW and 20 MW. Furthermore the minimal amount of heat that has to be sold to make combined heat and power production more profitable than pure electricity production has been determined. By performing Monte Carlo simulations, key variables that influence the *NPV* have been identified.

In the case of small scale SRC conversion, i.e. at an electrical capacity of 5 MW–10 MW, flash pyrolysis is more profitable than gasification. At the smallest scale of 5 MW it is necessary to invest in combined heat and power production, as the sole production of electricity is not profitable at this low scale. At an electrical capacity of 10 MW flash pyrolysis for the sole production of electricity becomes profitable, but gasification for electricity production is still not viable. At this capacity however, the extra investments required in the case of combined heat and power production are already paid back if only 25% of the produced heat can be sold. At a higher capacity of 20 MW, the technology choice becomes unclear taking into account the most uncertain variables, i.e. investment cost parameters and energetic efficiencies.

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1. Introduction

Short rotation coppice (SRC) seems to be an attractive source of income for farmers as an energy crop on marginal land [1–3]. SRC are dense plantations of 10,000 to 20,000 cuttings per hectare of fast growing trees like willow and poplar [4]. Seven to eight rotation lengths of 3 years each are often applied, after which biomass production decreases significantly [4–6]. The energy content of SRC is between 17 MJ kg^{-1} dry willow and 19 MJ kg^{-1} dry willow [7]. The net energy output for willow is expected to be higher than for poplar when field drying is applied up to a final moisture content of

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25%: 4% of dry matter is lost for willow while 13% of dry matter is lost for poplar [8]. Therefore further calculations are based on willow, which has a biomass yield between 10 Mg ha^{-1} y^{-1} and 12 Mg ha^{-1} y^{-1} [9]. Taking into account the loss of dry matter of 4% during field drying at the lower end of the biomass yield range, a dry willow yield of 9.6 Mg ha^{-1} y^{-1} with an averaged lower heating value of 18 MJ kg^{-1} dry willow [10] has been used throughout this article.

SRC can be converted into energy by thermal conversion techniques such as combustion, gasification and pyrolysis [10]. Both biomass integrated gasification/combined gas-steam cycles and flash pyrolysis for electricity and/or heat production have not yet been reported as operating at a commercial scale [11]. Earlier studies indicated that biomass integrated gasification and flash pyrolysis are expected to perform energetically and economically better than combustion [12,13]. Furthermore flash pyrolysis has the advantage that willow conversion and energy production can be decoupled. The profitability of these conversion technologies “in development” for willow, i.e. gasification and flash pyrolysis, is compared by calculating the net present value (*NPV*) of the cash flows realized by each investment in order to identify the circumstances under which both conversion technologies render themselves profitable. The *NPV* has been calculated and compared for (combined heat and) power stations with an electrical capacity between 5 MW and 20 MW because most of the existing biomass gasification or pyrolysis plants are situated in this range [14–16]. Moreover, due to limitations in biomass availability in Flanders, larger biomass conversion plants are not feasible.

2. Conversion technology assumptions

2.1. *Pretreatment*

Willow needs to be dried and reduced in size for the conversion in a gasification and pyrolysis reactor. Maximal moisture contents between 10% and 20% and wood chip sizes of 25 mm–30 mm are required for the well functioning of a fluid bed gasifier [10]. For flash pyrolysis more stringent willow feedstock properties are imposed. A maximal moisture content of 5%–10% is required and the willow feedstock needs to be grinded to the size of 2 mm in order to ensure an efficient heat transfer [10,17].

2.2. *Gasification*

In applications with an electrical capacity of 5 MW, mostly fluid bed configurations are being considered [10,18]. Biomass integrated gasification and combined gas-steam power cycle (IGCC) is a promising concept with a high overall conversion efficiency up to 40%–50% [11,13,18–20].

Fig. 1 illustrates the assumptions for a gasification plant with an electrical capacity of 5 MW or, based on the assumption of 7000 operational hours per year, 126 TJ y^{-1}. The overall electrical efficiency of a gasification plant ($\alpha_{e,\ gas}$) of 5 MW is assumed to be 36% [18]. Hence, to produce 126 TJ y^{-1} of electrical energy, 350 TJ y^{-1} or 19 Gg y^{-1} of dry willow is required. Since the gasification plant is operational during 7000 h y^{-1}, this means that the gasification plant should convert 2.78 Mg h^{-1} of dry willow for the electricity production of 126 TJ y^{-1}. If one invests in heat exchangers for the CHP plant, one is also able to recuperate 140 TJ y^{-1} (i.e. a thermal capacity of 5.56 MW) heat from the steam and gas plant under the assumption that the overall thermal efficiency of the gasification plant ($\alpha_{th,\ gas}$) is 40% [21].

For larger gasification plants with an electrical capacity of 10 MW or 20 MW, the same basic model has been used. However, the electrical efficiency increases with the electrical capacity of the plant. For a gasification plant with an electrical capacity of 10 MW, the overall electrical efficiency ($\alpha_{e,\ gas}$) equals 39% while $\alpha_{e,\ gas}$ equals 41% for a 20 MW gasification plant [18].

2.3. *Flash pyrolysis*

Fluid bed pyrolysis is one of the main technologies of fast pyrolysis [22,23]. Bio-oil for internal combustion engines appears to be the most competitive with conventional energy production in terms of annual costs in Belgium [24].

Fig. 2 shows that willow is first converted into pyrolysis oil, biogas and char in a fluidized bed pyrolysis reactor. Subsequently, pyrolysis oil is burnt in an internal combustion engine to produce energy. In accordance with Fig. 1 for gasification, Fig. 2 schematizes the main assumptions for electricity production with an electrical capacity of 5 MW (or 126 TJ y^{-1}) above the dotted line. It is assumed that the internal combustion engine has an electrical efficiency of 43.5% at an electrical capacity of 5 MW [25]. So to produce 126 TJ y^{-1} of electrical energy, 290 TJ y^{-1} of pyrolysis oil is required. It is assumed that the energy density of pyrolysis oil is 15 GJ Mg^{-1} [26], based on a lower heating value of 18 GJ l^{-1} [17] and a mass density of 1.2 kg m^{-3} [27]. Therefore, the requirement of 290 TJ y^{-1} of pyrolysis oil corresponds to a pyrolysis oil production of 19 Gg y^{-1}. Under the assumption of a weight fraction of 70% [22] for the yield of pyrolysis oil, an input of dry willow feedstock of 28 Gg y^{-1} to the fluidized bed reactor is required. Because it is assumed that the flash pyrolysis plant is operational during 7000 h y^{-1}, this plant should convert 3.94 Mg h^{-1} dry willow for the electricity production of 126 TJ y^{-1}. If one invests in heat exchangers for the CHP plant, one is also able to recuperate 145 TJ y^{-1} (i.e. a thermal capacity of 5.75 MW) of heat under the assumption that the thermal efficiency of the internal combustion engine ($\alpha_{th,\ int\ comb}$) is 50% [28].

For a pyrolysis plant with an electrical capacity of 10 MW, the electrical efficiency of the internal combustion engine ($\alpha_{e,\ int\ comb}$) equals 45.1% while $\alpha_{e,\ int\ comb}$ equals 46.7% for a 20 MW pyrolysis plant [25].

3. Economic framework

3.1. *Economics of SRC conversion*

The available (techno-)economic assessments considered most relevant are briefly summarized below.

Mitchell et al. [12] developed a spreadsheet for the techno-economic assessment of short rotation forestry to electricity by gasification, fast pyrolysis and combustion (amongst others). Pyrolysis was the cheapest up to an electrical capacity of 20 MW. At higher scales gasification showed cost advantages

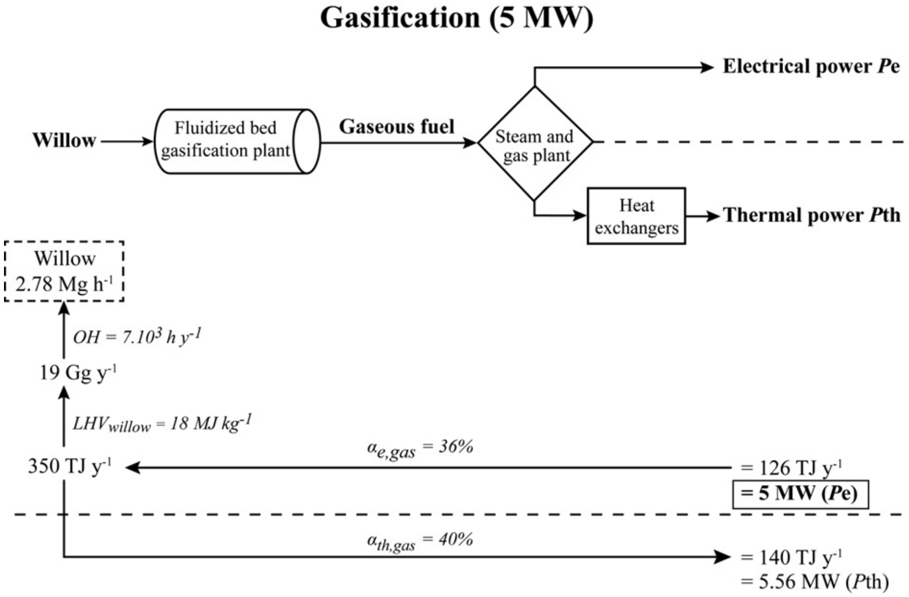

Fig. 1 – The gasification process.

despite the higher capital cost, thanks to its higher electrical efficiency. Above an electrical capacity of 50 MW however diseconomies of scale appeared for both gasification and pyrolysis. At all scales combustion was the most expensive conversion route.

Bridgwater et al. [10] also assessed the techno-economic performance of combustion, gasification and fast pyrolysis to generate electricity from wood chips for electrical capacities of 1 MW–20 MW. The fast pyrolysis and engine system generates electricity at the lowest cost at small scales up to an electrical capacity of 5 MW, whereas gasification is the least expensive for higher capacities.

Ringer et al. [17] determined the cost of bio-oil in a large-scale plant that produces 16 ton bio-oil per day. Bio-oils currently under production (i.e. heavy bio-oils with high viscosity) appear to be produced at a cost of 4.75 \$ Mg^{-1} dry matter if the bio-oil yield can be increased from a weight percentage of 60%–70% and if contingency costs can be reduced.

Caputo et al. [18] developed very detailed models for the comparison of the *NPV* of combustion and gasification for electricity production from agricultural crops byproducts, agro-industrial and wood wastes. Combustion breaks even at an electrical capacity of 25 MW and gasification only breaks even at 30 MW. At any size combustion reaches a higher *NPV* than

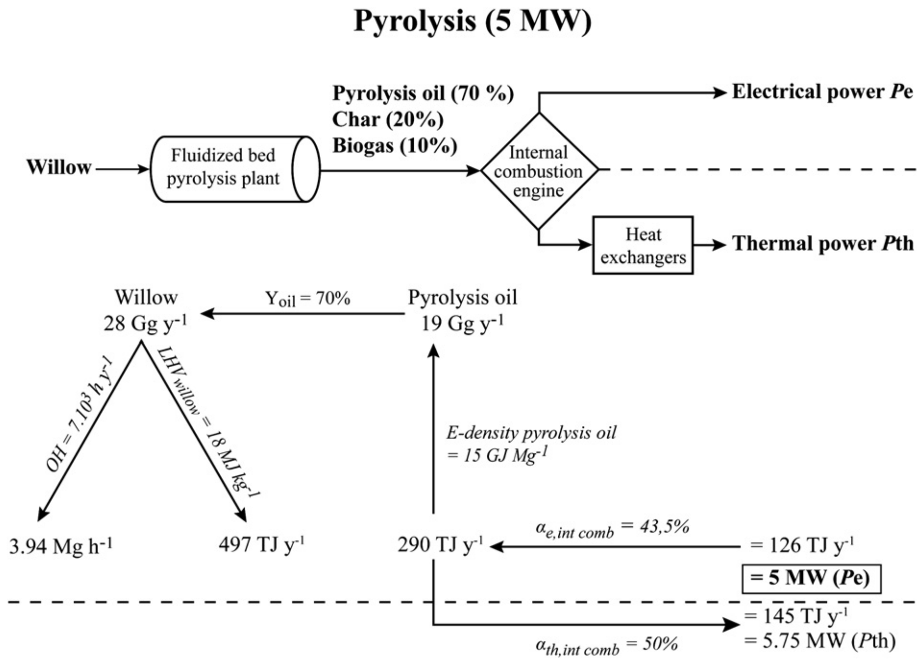

Fig. 2 – The pyrolysis process.

gasification, due to the higher capital costs incurred in the case of gasification, contradicting the results obtained in [10,12].

Dornburg et al. [13] evaluated the economics of wood-fired energy systems for heat and power generation using several combustion and gasification technologies. They concluded that combustion technologies cannot compete with gasification technologies with respect to both economic and energetic performance.

The main conclusion is that pyrolysis appears to be better suited for small capacities and gasification for higher capacities. However in literature the changeover point where gasification becomes more economical than pyrolysis differs. Therefore the current model adapts existing models to Flemish conditions. Additionally it has been investigated whether CHP production might enhance profitability of gasification and flash pyrolysis of SRC.

3.2. *Net present value calculation*

It is assumed that an enterprise will invest in *either* gasification *or* flash pyrolysis in order to process short rotation coppice cultivated on degraded land. Both alternatives thus are assumed to be mutually exclusive. Investment decisions for mutually exclusive alternatives are best based on the net present value method [29].

The economic model that has been developed for the calculation of the *NPV* of gasification and flash pyrolysis of short rotation coppice is summarized in Table 1.

In order to improve the readability of this article, Table 2 summarizes some concepts and abbreviations used in the next sections of this paper. The choice of the values will be explained and justified in more detail in the next sections.

4. Base case assumptions

In Section 4.1 the cash flows of electricity production are inventoried and explained. Section 4.2 deals with the cash flows of CHP production, based on the equations of Table 1. The values of the different variables are found in Table 2.

4.1. *Electricity production*

4.1.1. *Initial net investment*

The initial net investment (I_0) of both conversion techniques is calculated by subtracting the investment subsidy (U_{inv}) from the total investment costs (I).

Caputo et al. [18] have developed a model in which the total investment costs for a fluidized bed gasifier and a steam and gas plant are divided into different cost components like equipment, piping, electrical, civil works and installation costs. The costs are functions of the form aS^b in which a and b are specific coefficients and S is a characterizing variable like for example the capacity of the gas turbine in the steam and gas plant to calculate the cost of the turbogas group. No significant differences were found comparing cost estimates with actual cost data from vendors [18]. Economies of scale are included in the Caputo model which can be deducted from the value of b (always lower than 1).

Bridgwater et al. [10] have developed equations to calculate the total investment costs of gasification for electricity production. Calculations of the total investment costs based on [10] and [18] resulted in similar values. Because the Caputo model enables to determine the size of the different cost components (which are important for the determination of the amount of investment subsidies) and because it covers a wider load of literature references than Bridgwaters equations, the total investment costs for gasification are based on the Caputo model and indexed to cost values of June 2009 by applying the chemical engineering plant cost index [43].

The total investment costs of pyrolysis consist of the investment cost of the fluidized bed pyrolysis reactor, the storage costs of the pyrolysis oil and the investment costs of the internal combustion engine. The investment costs of the fluidized bed reactor, which include the costs of the fast pyrolysis reactor, the feeding system and liquids recovery,

Table 1 – Net present value calculation.

Category	Symbol	Formula
Net present value	NPV	$= \sum_{n=1}^{t} \frac{CF_n}{(1+i)^n} - I_0$
Cash flow in year n	$\mathbf{CF_n}$	$= (1-\tau) \times (R_n - E_n) + \tau \times D_n$
Revenues in year n	$\mathbf{R_n}$	$= R_{elec} + R_{gcc} + R_{heat} + R_{hpc}$
Revenues from the sales of electricity	R_{elec}	$= p_{s\ elec} \times (P_e - P_{int}) \times OH$
Revenues from the sales of green current certificates	R_{gcc}	$= p_{gcc} \times P_e \times OH$
Revenues from the sales of heat	R_{heat}	$= p_{s\ heat} \times P_{th} \times OH$
Revenues from the sales of combined heat and power certificates	R_{hpc}	$= p_{hpc} \times P_e \times OH$
Expenditure in year n	$\mathbf{E_n}$	$= FC + VC$
Fixed costs	FC	$= \epsilon_{FC} \times I$
Variable costs	VC	$= c_{labor} + c_{willow} + c_{ash/char} + c_{water}$
Staff costs	C_{staff}	$= w \times N$
Supply costs willow	C_{willow}	$= Q_{dry} \times OH \times (c_{pre} + c_{purch} + c_{trans})$
Transport and treatment costs of the byproducts	$C_{ash/char}$	$= Q_{ash/char} \times Q_{dry} \times OH \times (c_{tran\ ash/char} + c_{disp})$
Costs of energy and water	C_{water}	$= p_{water} \times Q_{water}$
Tax shield depreciation	$(\tau \times D_n)$	$= \tau \times (I/t)$
Initial net investment	I_0	$= I - U_{inv}$
Total investment costs (I)		$= I$, based on [10,18,30]
Investment subsidy	U_{inv}	$= \beta \times I_{ess}$

Table 2 – Base case variables.

Abbreviation	Variables and explanation	Value gasification	Value pyrolysis
b	Specific coefficient of total investment costs	Variable [18]	Variable [10]
c_{disp}	Disposal cost of the byproducts (ashes/char)	62 € Mg^{-1} dry willow [18]	/
$c_{heat\ distrib}$	Specific cost of heat distribution	18 € Mg^{-1} km^{-1} [13]	18 € Mg^{-1} km^{-1} [13]
c_{pre}	Pretreatment cost of drying and cutting willow	20 € Mg^{-1} [24,31,32]	26.66 € Mg^{-1} [31–33]
c_{purch}	Purchase cost of dry willow	50 € Mg^{-1} [34]	50 € Mg^{-1} [34]
c_{trans}	Transport cost of dry willow	Variable	Variable
$c_{trans\ ash/char}$	Transport cost of the byproducts (ashes/char)	24 € Mg^{-1} dry willow [18]	/
CF_n	Cash flow in year n	Variable	Variable
D_h	Density of heat demand	2.2 MW km^{-2} [13]	2.2 MW km^{-2} [13]
D_n	Yearly depreciation (€ y^{-1})	Variable	Variable
E_n	Cash expenditure in year n	Variable	Variable
i	Discount rate after taxes	6.67% [35]	6.67% [35]
I	Total investment costs	Variable	Variable
I_{ess}	Essential investment components	Variable	Variable
$I_{heat\ distrib}$	The investment cost of heat distribution	Variable [13]	Variable [13]
I_0	The initial net investment	Variable	Variable
$LHV_{pyr\ oil}$	Lower heating value of pyrolysis oil	/	18 GJ l^{-1} [17]
LHV_{willow}	Lower heating value of willow	18 GJ Mg^{-1} [10,28]	18 GJ Mg^{-1} [10,28]
N	Total number of employees in the conversion plant	Variable [10]	Variable [10]
NPV	Net present value	Variable	Variable
OH	The number of operating hours per year	7000	7000
p_{gcc}	Market price for green current certificates	106.87 € MWh^{-1}	106.87 € MWh^{-1}
p_{hpc}	Market price for heat and power certificates	37.32 € MWh^{-1}	37.32 € MWh^{-1}
$p_{p\ elec}$	Purchase price of electricity	72.5 € MWh^{-1} [36]	72.5 € MWh^{-1} [36]
$p_{s\ elec}$	Sales price of electricity	50 € MWh^{-1} [34]	50 € MWh^{-1} [34]
$p_{s\ heat}$	Sales price of heat	20 € MWh^{-1} [36]	20 € MWh^{-1} [36]
p_{water}	Purchase price of water	1.50 € m^{-3} [10]	1.50 € m^{-3} [10]
P_e	Power (electrical) of the installation in MW	Variable	Variable
$P_{int,\ comb}$	Power (electrical) that is needed internally in the internal combustion engine	/	3% of P_e [10]
$P_{int,\ fluid\ bed}$	Power (electrical) that is needed internally in the fluidized bed reactor	40 kWh Mg^{-1} dry willow [10]	4 kWh Mg^{-1} dry willow [10]
$P_{int,\ steam\ and\ gas}$	Power (electrical) that is needed internally in the steam and gas plant	3% of P_e [10]	/
P_{th}	Power (thermal) of the installation in MW	Variable	Variable
$Q_{ash/char}$	Hourly flow ratio of the byproducts (ashes/char)	2% of Q_{dry} [18]	/
Q_{dry}	Hourly flow ratio of the dry willow feedstock (Mg h^{-1})	Variable	Variable
Q_{water}	Amount of cooling water	2.1 Mg MWh^{-1} electricity produced [10]	18.5 m^3 Mg^{-1} dry willow [10]
R_n	Cash revenues in year n	Variable	Variable
t	Project duration in years	20 [37,38]	20 [37,38]
τ	Tax rate levied on profits	33% [39]	33% [39]
w	Annual cost of labor per employee	52 k€ [40,41]	52 k€ [40,41]
Y_{gas}	Weight fraction of dry willow converted into biogas during pyrolysis	/	10% [22]
Y_{char}	Weight fraction of dry willow converted into char during pyrolysis	/	20% [22]
Y_{oil}	Weight fraction of dry willow converted into pyrolysis oil during pyrolysis	/	70% [22]
Y_{willow}	Yearly amount of harvested willow after field drying	9.6 Mg ha^{-1} yr^{-1} [8]	9.6 Mg ha^{-1} yr^{-1} [8]
β	Factor of investment subsidy on essential investment components	5%	5%
ρ	The mass density of pyrolysis oil	/	1.2 kg m^{-3} [27]
ϵ_{FC}	Fixed costs (% of investment) for maintenance, insurance and overheads	4% [18]	7.5% [42]

and the storage costs, which include the cost of the liquid storage tanks and transfer pumps, are calculated using equations from Bridgwater et al. [10]. The investment cost of the internal combustion engine is calculated using an equation that was developed by Thewys and Kuppens [30].

The equations for estimating the investment cost of pyrolysis are also of the form: aS^b. Again economies of scale are assumed in the different equations because the value of b is always lower than 1. The different cost equations to calculate the investment costs of pyrolysis are also indexed to cost values of June 2009 by applying the chemical engineering plant cost index [43].

Companies that invest in a biomass conversion plant in the Flemish Region are granted an investment subsidy for the additional investments that are necessary for the accomplishment of environmental goals, the so-called “essential investment components”. The percentage of the investment subsidy on the essential investment components is 5%.

4.1.2. *Expenditure*

Maintenance, insurance and general overhead costs are fixed costs that are expressed as a percentage of the investment cost: 4% [18] for gasification and 7.5% [42] for pyrolysis.

Variable costs consist of labor costs, supply costs of willow, transport and treatment costs of the byproducts and costs of energy and water consumption.

Total annual staff costs are the product of the annual wage (w) of 52 k€ [40,41] and the total number of employees (N) calculated following [10].

The supply cost of willow is the sum of its purchase cost (c_{purch}), its transport cost (c_{tran}) and its pretreatment cost (c_{pre}). The purchase cost of dry willow is 50 € Mg^{-1} [34]. The transport cost (€ Mg^{-1}) of dry willow increases with the amount of willow that has to be supplied, because the travel distance increases. The specific transport cost of dry willow, based on Fiala et al. [44], taking into account the increase of the average diesel price is 0.43 € Mg^{-1} km^{-1}. Drying costs are typically in the range of 7 € Mg^{-1} input to 12 € Mg^{-1} input [31–33]. Grinding costs are somewhat unclear: a range between 2 € Mg^{-1} dry willow [17] and 20 € Mg^{-1} dry willow [31] is found [17,31–33,45]. Chipping would be 50% cheaper than grinding. In this study, both the cost of drying and grinding is set at 10 € Mg^{-1} dry willow. The cost of chipping is 5 € Mg^{-1} dry willow.

The ashes that are left after the gasification process are transported and disposed at a cost of 24 € Mg^{-1} dry willow [18] while the char that is produced during the pyrolysis process is combusted to provide the pyrolysis reactor with electricity.

The cost of the cooling water in the gasification process varies with the amount of electricity that is produced. The gasification plant requires an amount of 2.1 Mg of water per MWh electricity produced. The pyrolysis installation uses on average 18.5 m^3 cooling water per Mg of willow that is fed into the reactor. The price of water is 1.50 € m^{-3} [10].

For gasification, the electricity produced is used to provide the process with electricity. For pyrolysis, the electricity that is needed for the provision of the fluidized bed pyrolysis reactor and the internal combustion engine is generated by the combustion of the char that is produced during the pyrolysis process. Electricity needs of the pyrolysis process can be fully satisfied by the combustion of char. Based on [10], it is assumed that the heat needs of the pyrolysis process are met by the internal combustion of the non-condensable biogas. Note that the investment costs for pyrolysis (see section 4.1.1) include the investment cost of a biogas combustor.

4.1.3. *Revenues*

It is assumed that all electricity produced can be sold to the grid. In the case of gasification, the amount of electricity required in the gasification process is subtracted from the total amount of electricity produced. As the pyrolysis process is provided with electricity by the combustion of char, all electricity produced with pyrolysis oil is available for sale.

In Flanders, green current certificates are awarded for each MWh of electricity produced from renewable energy sources. The electricity producers can sell their certificates to electricity suppliers. The sales price of the green current certificates in Table 2 is the average sales price of September 2010.

4.2. *Combined heat and power production*

4.2.1. *Initial net investment*

In comparison with Section 4.1.1 the investment cost of gasification and pyrolysis increases because heat exchangers are required to recover low-grade heat and because the heat has to be distributed to the customer. For gasification, the heat exchangers make up 5% of the total investment costs. For pyrolysis, the additional investment in heat exchangers is 10% of the investment costs of the internal combustion engine [46].

It is assumed that the heat is distributed in a residential area that has a higher than average heat density (D_{h}) of 2.2 MW km^{-2}. The investment cost of heat distribution is determined by Eq. (1) with a specific cost for the distribution of heat ($C_{\text{heat distrib}}$) of 18 € MJ^{-1} km^{-1} [13].

$$I_{heat\ distrib} = C_{heat\ distrib} \times S_d P_{th} \tag{1}$$

$S_d P_{th}$ is the average amount of heat distributed multiplied by the distance for distribution (in MJ × km y^{-1}) and is calculated by Eq. (2). The amount of heat distributed ($Q_{\text{heat distr}}$)is expressed in MJ yr^{-1} while the operational time equals 7000 h y^{-1}.

$$S_d P_{th} = \frac{2}{3}(Q_{heat\ distrib})^{1.5}(3600 \times D_h \times OH \times \pi)^{-0.5} \tag{2}$$

The investment subsidy is calculated in the same way as in Section 4.1.1. Note however that in the case of CHP production the investment must meet some conditions concerning the electrical and thermal efficiency of the CHP plant that are imposed by the Belgian Ministry of Finance.

4.2.2. *Expenditure*

Expenditure is calculated in the same way as in Section 4.1.2. The fixed costs rise because they are directly correlated with the total investment costs. The variable costs are equal to the situation in which only electricity is produced.

4.2.3. *Revenues*

The revenues from the sales of electricity and the sales of green current certificates are calculated in the same way as in Section 4.1.3. Note that it is assumed here that all heat produced is sold on the market.

CHP producers receive combined heat and power certificates for the primary energy savings (PES) they realize in the Flemish Region by means of a qualitative CHP installation. A CHP installation is qualitative when, on average, it realizes primary energy savings of at least 10% during the last 12 months in comparison with the reference installations for the separate production of electricity.

Each combined heat and power certificate shows that 1 MWh of primary energy was saved in a qualitative CHP installation. The sales price of the combined heat and power certificates in Table 2 is the average price of September 2010.

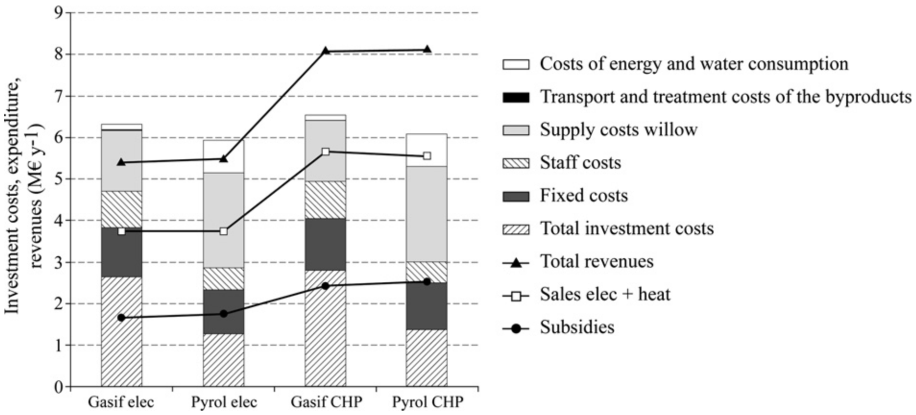

Fig. 3 – Yearly expenditure and revenues 5 MW.

The number of CHP certificates that are granted diminishes as the lifetime of the installation increases [47].

5. Economic analysis base case

The profitability of an investment in gasification and pyrolysis is compared for an electrical capacity of 5 MW, 10 MW and 20 MW by means of Figs. 3 to 5. Each figure shows the yearly expenditure and yearly revenues of the investment in either gasification or pyrolysis for either electricity or CHP production. Since the economic analysis of the base case is performed on an annual basis, total investment costs per year were calculated as an annuity and added in the bar charts.

5.1. *Initial net investment*

For the entire capacity range (see Figs. 3 to 5) the investment in gasification for electricity production is more than twice as expensive as the investment in pyrolysis. As mentioned in Section 4.2.1, in comparison with the situation in which only electricity is produced, the investment cost of a CHP plant increases for both techniques because of an extra investment for additional heat exchangers and for the distribution of the heat produced. The extra investment costs for CHP production are the highest for gasification because of higher thermal efficiencies compared to flash pyrolysis. The higher the heat production, the larger the required heat distribution network and the larger the capacity of the additional heat exchanger.

5.2. *Expenditure*

For the entire capacity range, yearly expenditure (excluding the investment expenditure) is the highest for pyrolysis due to a lower electrical efficiency in comparison with gasification, which implies that more willow has to be supplied to the pyrolysis plant than to the gasification plant to generate the same amount of electricity. As can be seen in Figs. 3 to 5, this evidentially results in higher willow supply costs for pyrolysis. Because the pyrolysis process requires more water consumption for the rapid cooling of the product gases for the production of bio-oil, costs of energy and water consumption are higher for a pyrolysis plant.

5.3. *Revenues*

Revenues are represented in Figs. 3 to 5 by three superimposed lines. The upper line represents the total revenues. Furthermore, the sales of electricity and heat (in the case of CHP production) are represented by a single line. The same goes for the subsidies that are granted to the investor. In the case of electricity production, subsidies consist of green current

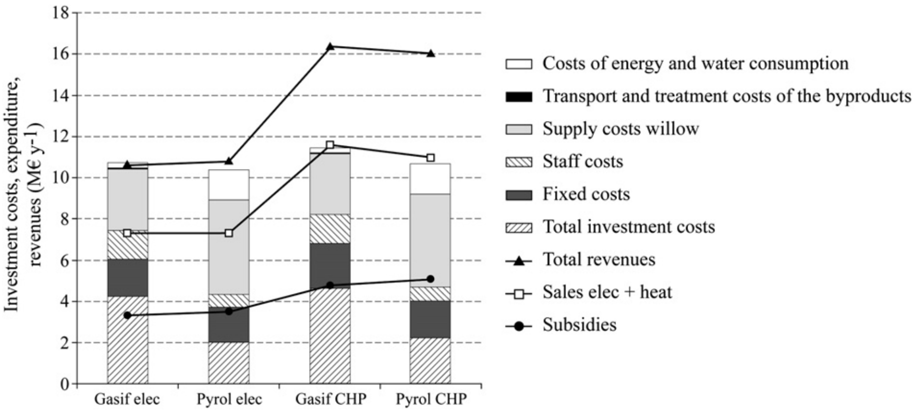

Fig. 4 – Yearly expenditure and revenues 10 MW.

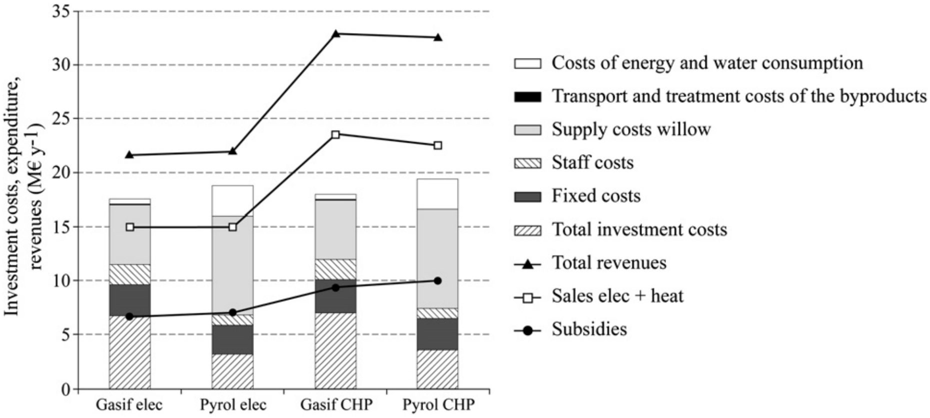

Fig. 5 – Yearly expenditure and revenues 20 MW.

certificates while for CHP production combined heat and power certificates also make part of the subsidies. Note that the upper line equals the sum of the middle and the lower line.

For the entire capacity range, the revenues from the sales of electricity and heat (in the case of CHP production) are slightly higher for pyrolysis because the electricity produced during gasification is used to provide the gasification process with electricity whereas the pyrolysis process is provided with electricity by char combustion.

When only electricity is produced, subsidies are equal for both techniques. In the case of CHP production, subsidies are slightly higher for gasification because the amount of combined heat and power certificates is based on electrical efficiency and the latter is higher in the case of gasification.

From Figs. 3 to 5, it can be concluded that subsidies are significantly higher than the revenues from the sales of electricity and heat (in the case of CHP production). When no subsidies are granted, the revenues from the sales of electricity and heat (in the case of CHP production) do not cover the sum of the investment costs per year and the yearly expenditure.

5.4. *Net present value*

If the upper revenue line of the total revenues in Figs. 3 to 5 lies higher than the bar that represents the sum of the investment costs per year and the yearly expenditure, the *NPV* is positive.

Since the difference between the upper revenue line and the investment and expenditure bar in Figs. 3 to 5 is larger for CHP production than for electricity production, it can be concluded that for the entire capacity range and for both gasification and pyrolysis, the *NPV* is the highest for CHP production. This means that the additional revenues from the sales of heat and combined heat and power certificates outweigh the required additional investment expenditure. Fig. 3 shows that for an electrical capacity of 5 MW, the investment in gasification or pyrolysis for electricity production results in a negative *NPV*. The *NPV* of gasification for electricity production is even more negative than that of pyrolysis. In the case of CHP production, the upper revenue line exceeds the investment and expenditure bar for both gasification and pyrolysis, but the *NPV* is the highest for pyrolysis. Therefore, in the case of an electrical capacity of 5 MW, the most profitable situation is attained by the investment in a pyrolysis CHP plant.

In the case of an electrical capacity of 10 MW (see Fig. 4) it can be concluded that the investment in gasification for electricity production results in a negative *NPV*. In the case of electricity production by pyrolysis, the *NPV* is positive. The *NPV* of the investment in CHP is positive for both gasification and pyrolysis, but the most profitable situation for an electrical capacity of 10 MW is attained by the investment in a pyrolysis CHP plant.

Fig. 5 shows that an investment in either a gasification or pyrolysis plant with an electrical capacity of20 MW results in positive *NPV* for either electricity or CHP production. The difference between the upper revenue line and the investment and expenditure bar is for both electricity and CHP production the highest for gasification. Consequently, for an electrical capacity of 20 MW the investment in gasification appears to be more attractive than the investment in pyrolysis for either electricity production or heat and power production.

6. Scenario-analysis

In the base economic model (see Section 5), it was assumed that all heat produced was sold on the market. However, this assumption might be too optimistic because heat demand is dependent on the season. The *NPV* is now calculated for CHP installations when 25%, 50%, 75% and 100% of the heat produced is sold. This way, it will be possible to determine the minimal amount of heat that has to be sold in order to make the investment in CHP production more profitable than the investment in electricity production solely.

The cash expenditure is equal for all scenarios as it is assumed ex ante that all heat produced can be sold. However, as just mentioned, the ex post amount of heat that can be sold may be disappointing. Furthermore, one does not always obtain subsidies because they depend on the amount of electricity and heat that is actually sold on the market. As can be seen in Table 3, which is valid for both gasification and pyrolysis, at least 75% of the heat produced must be sold on the market to obtain an investment subsidy. Since for each

Table 3 – Investment subsidy and CHP certificates scenario-analysis.

Scenario	Heat sales (%)	Eligible for investment subsidy?	Qualitative CHP?
1	25	No	Yes
2	50	No	Yes
3	75	Yes	Yes
4	100	Yes	Yes

scenario primary energy savings are higher than 10%, CHP certificates are always granted.

6.1. Net present value scenarios

Figs. 6, 7 and 8 reproduce the *NPV* generated by an investment in either gasification or pyrolysis for either electricity or CHP production, taking into account disappointing heat sales in the latter case.

In Fig. 6 the *NPV* for an electrical capacity of 5 MW is shown for all scenarios. As already mentioned in Section 5.4, the sole production of electricity is not profitable at an electrical capacity of 5 MW, nor by means of gasification, nor by flash pyrolysis. For gasification the investment in CHP production is only profitable when all heat produced is sold. For pyrolysis, at least 50% of the heat produced should be sold on the market to generate a positive *NPV*.

In Fig. 7 the *NPV* for an electrical capacity of 10 MW is shown for all scenarios. The sole production of electricity is only profitable by means of flash pyrolysis. Gasifying SRC at an electrical capacity of 10 MW is still not profitable. However, if only 25% of the heat produced can be sold on the market, the *NPV* becomes positive in the case of gasification. For flash pyrolysis, 25% heat sales are also sufficient to generate a higher *NPV* than in the case only electricity is produced.

In Fig. 8 the *NPV* for an electrical capacity of 20 MW is shown for all scenarios. Again, if 25% of the produced heat can be sold, the revenues of CHP production already exceed the extra investments and other expenditure required for CHP. In other words, a minimal amount of heat sales suffices to render CHP production more profitable than the sole production of electricity.

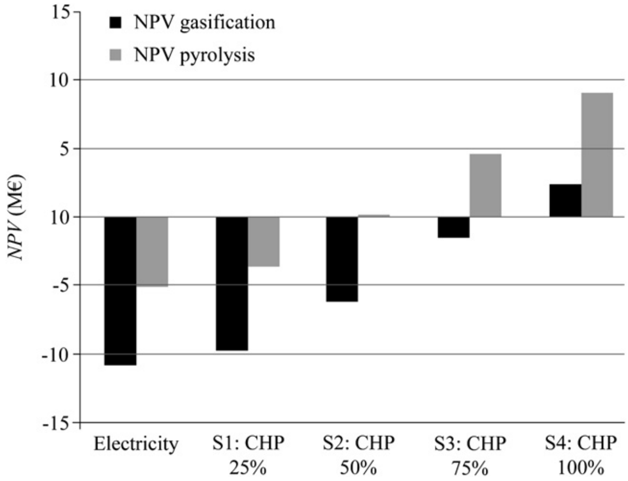

Fig. 6 – Net present value 5 MW.

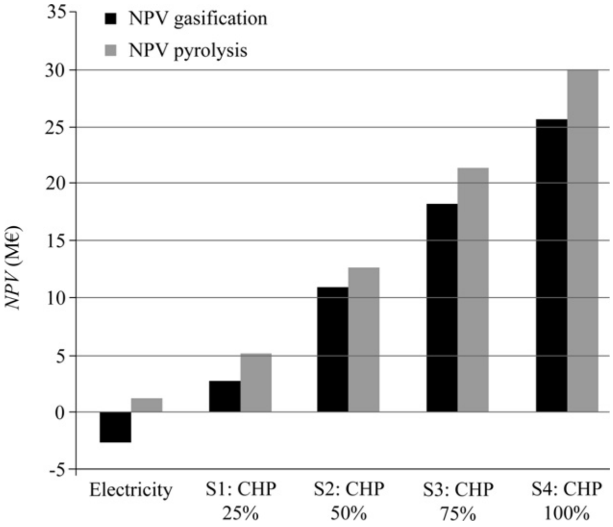

Fig. 7 – Net present value 10 MW.

7. Sensitivity analysis

So far, calculations of the *NPV* are based on the values of the variables shown in Table 2, but some variables are uncertain by definition or have an important influence on the *NPV*. Using Monte Carlo simulation (5000 trials), these variables are varied following a triangular distribution with a maximal positive or negative change of 10%. The following variables have been identified for both gasification and pyrolysis: electrical efficiency, sales price of electricity, sales price of heat (only for CHP) and purchase cost of short rotation coppice. For gasification, the specific coefficient *b* (see Section 4.1.1) of the four most important investment components has also been selected, being the gasifier, the turbogas group, the heat-recovery dryer and civil works. For pyrolysis, the specific coefficient *b* of the equations to calculate the total investment costs of the fluidized bed reactor and the internal combustion engine has been selected.

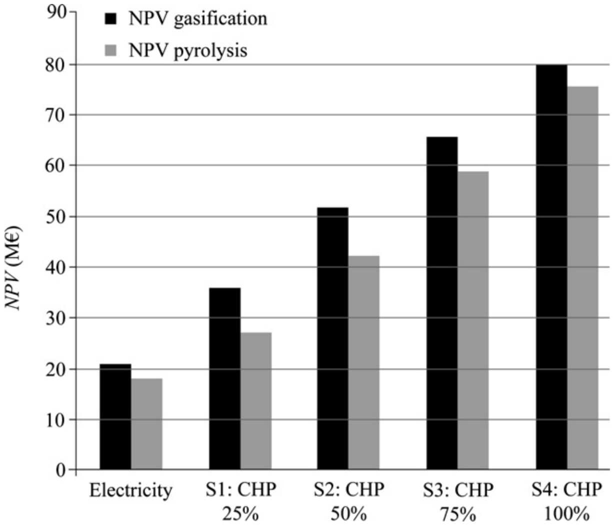

Fig. 8 – Net present value 20 MW.

Note that the height of the specific coefficient *b* determines the size of the economies of scale of an investment. An increase of the coefficient results in smaller economies of scale, while a decrease of the coefficient results in larger economies of scale. As the specific coefficient *b* is the result of regression analyses performed by Caputo and Bridgwater, other data sources would have resulted in other values for *b*. Therefore the impact of the variability (e.g. an increase or a decrease with 10%) of coefficient *b* has been investigated. A 10% increase of *b* results in an increase of the average investment cost of the gasifier by about 100% while a 10% decrease of *b* results in a decrease of the investment cost of the gasifier by about 50%. It is unlikely that estimation errors of this order of magnitude occur in practice. The expected accuracy for study estimates of investment costs in chemical processes is in the ±20%–30% range [48].

For the determination of the expected *NPV* under uncertainty, therefore a ±30% range for the estimates of investment costs is allowed. Consequently, the specific coefficients that were selected to be subjected to a sensitivity analysis are increased and decreased by a percentage that results in a ±30% range of their corresponding investment cost component. For example, a 30% decrease of the investment cost of the gasifier is caused by a decrease of the specific coefficient by 4.2%. A 30% increase of the investment cost of the gasifier is caused by an increase of the coefficient b of 4.4%. Therefore, in the analysis, the specific coefficient of the gasifier will be increased by a maximum percentage of 4.4% and decreased by a maximum percentage of 4.2%. An analogous reasoning was followed for all investment components, also for the pyrolysis case.

7.1. *Sensitivity of the* NPV

First, the relative influence of the different variables on the *NPV* has been examined for a conversion plant with an electrical capacity of 5 MW. Then, three important statistical measures considering the distribution of the *NPV* are analyzed.

As can be seen in Table 4, the largest part of the variance in *NPV* for gasification is due to a change in the specific coefficient *b* of the components of the total investment costs. Lower values of the coefficients *b*, representing stronger economies of scale, have a large positive influence on the level of the *NPV*. Especially the coefficient of the turbogas group component exercises a huge impact on the *NPV*. Note that the specific coefficient of both the heat-recovery dryer and civil works have a considerably smaller influence on the *NPV* than the specific coefficient of the gasifier and the turbogas group. When only electricity is produced, 19.9% of the variance in *NPV* is explained by a change in electrical efficiency. For CHP production this percentage increases to 32.1%. The sales price of electricity and heat and the purchase cost of short rotation coppice together explain less than 10% of the variance in the *NPV*. The variables in Table 4 with a positive sign have a positive influence on the *NPV* when the value of that variable is increased. When a variable has a negative sign, this means that the increase of the value of that variable exercises a negative influence on the *NPV*.

Table 4 – Relative contribution of the variables' range to the variance in *NPV* for gasification.

Variable	Relative contribution to *NPV* variance (%) for gasification	
	Electricity	CHP
Specific coefficient *b* gasifier	−14.4	−13.6
Specific coefficient *b* turbogas group	−42.5	−35.0
Specific coefficient *b* heat-recovery dryer	−8.3	−5.9
Specific coefficient *b* civil works	−5.3	−4.2
Electrical efficiency $\alpha_{e,\ total}$	19.9	32.1
Sales price electricity $P_{sales\ electricity}$	7.5	5.4
Sales price heat $P_{sales\ heat}$	/	1.1
Purchase cost short rotation coppice C_{purch}	−2.2	−1.7

In the case of the sole production of electricity by means of pyrolysis (see Table 5), the electrical efficiency of the process is the variable that exercises the largest influence on the *NPV*. In the case of CHP production, the specific coefficient *b* of the fluidized bed reactor is the variable that influences the *NPV* the most. Note that the specific coefficient of the internal combustion engine has a considerably smaller influence on the *NPV* than the coefficient of the fluidized bed reactor. Lower values of these two *b* coefficients, as mentioned representing larger economies of scale, have again a strong positive influence on the *NPV*. Just like with gasification, the sales price of electricity and heat and the purchase cost of short rotation coppice together explain less than 10% of the variance in the *NPV*.

7.2. *Impact of uncertainty*

If the values of all variables are certain (see Section 5) an investor will invest in the conversion technique with the highest net present value. Some variables however are uncertain by definition or have such a huge impact on the *NPV*, so that a slight change in the variable's value might cause a significant shift in the *NPV* and hence influence the investment decision. Depending on the risk-taking behavior of the investor, other factors become important in the decision making process. Choosing the technique with the highest *NPV* is not

Table 5 – Relative contribution of the variables' range to the variance in *NPV* for pyrolysis.

Variable	Relative contribution to *NPV* variance (%) for pyrolysis	
	Electricity	CHP
Specific coefficient *b* fluidized bed pyrolysis reactor	−34.9	−38.2
Specific coefficient *b* internal combustion engine	−12.8	−15.4
Electrical efficiency $\alpha_{e,\ total}$	44.1	36.6
Sales price electricity $P_{sales\ electricity}$	4.9	5.1
Sales price heat $P_{sales\ heat}$	/	1.2
Purchase cost short rotation coppice C_{purch}	−2.6	−3.5

Table 6 – Statistical measures sensitivity analysis for gasification.

	Gasification electricity			Gasification electricity & heat 100%		
(1) Electrical power installation (MW)	(2) Median *NPV* (M€)	(3) Percentual standard error of mean (%)	(4) Probability that *NPV* > 0	(5) Median *NPV* (M€)	(6) Percentual standard error of mean (%)	(7) Probability that *NPV* > 0
5	−10.6	1.24	0	2.6	1.16	88.73
10	−5.6	0.90	5.49	21.3	0.27	100
20	12.4	0.77	96.20	66.1	0.17	100

Table 7 – Statistical measures sensitivity analysis for pyrolysis.

	Pyrolysis electricity			Pyrolysis electricity & heat 100%		
(1) Electrical power installation (MW)	(2) Median *NPV* (M€)	(3) Percentual standard error of mean (%)	(4) Probability that *NPV* > 0	(5) Median *NPV* (M€)	(6) Percentual standard error of mean (%)	(7) Probability that *NPV* > 0
5	−4.6	0.71	2.18	9.6	0.33	100
10	−0.7	0.53	43.71	28.3	0.21	100
20	10.7	0.37	87.69	69.3	0.17	100

straightforward anymore, as uncertainties result in a distribution of possible net present values characterized by a mean/median value, by its variance and the certainty related to the sign of the net present value (either negative or positive).

In Tables 6 and 7, the median value of the *NPV* based on the 5000 trials is shown for both gasification and pyrolysis, as well for the combination with electricity production as for the combined production of power and heat, and this for all capacities (for reasons of simplification the heat sales scenarios have now been ruled out). Both tables also contain the percentual standard error of the mean *NPV* which is an indicator for the variance of the *NPV*. Thirdly, the probability that the *NPV* of the investment in gasification or pyrolysis is larger than zero is mentioned in Tables 6 and 7. This information should help investors in their decision making process. Risk averse investors might opt for the conversion technique with the smallest percentual standard error of the mean or the technique that has the highest probability to result in a positive *NPV*. Risk seeking investors might just choose the conversion technique that results in the highest median *NPV*.

Based on the *NPV* taking into account uncertainty, the most profitable situation for an electrical capacity of 20 MW is attained by the investment in a CHP plant for pyrolysis (see Tables 6 and 7, columns 2 and 5) while in the base case (see Fig. 8) it was concluded that the most profitable situation for an electrical capacity of 20 MW was attained by the investment in a CHP plant for gasification. Therefore, at an electrical capacity of 20 MW the choice of technology becomes somewhat unclear. In practice this means that an ad hoc analysis on the uncertain variables is required in order to be able to decide on the best technology.

The standard error of mean is a measure for the variance of the *NPV* distribution. It is obvious that the absolute standard error increases with a higher median *NPV*. Therefore, to improve the comparability of this measure for the different capacities, the standard error of mean is divided by the mean value of the *NPV* from 5000 trials in the sensitivity analysis. It is important to notice that the percentual standard error decreases with an increasing capacity of the installation (see Tables 6 and 7, columns 3 and 6). Hence, the certainty of the calculations of the *NPV* increases with the scale of the investment although it should be noted that the relative standard error is very low (maximum 1.24% in the case of gasification for electricity production at an electrical capacity of 5 MW, see column 3 of Table 6). However, at higher scales the uncertainty about the biomass supply increases.

In general, the probability that the *NPV* is positive increases with the capacity of the installation (see Tables 6 and 7, columns 4 and 7). However, note that for the sole production of electricity there still is a chance on a negative *NPV* at an electrical capacity of 20 MW (e.g. 13% for pyrolysis) despite the fact that the median value of the *NPV* might exceed millions of euros (e.g. 10.7 M€ for pyrolysis).

8. Conclusion

At an electrical capacity of 5 MW it is not profitable to invest in electricity production in Flanders. At this capacity, SRC conversion becomes only profitable when it is processed into heat and power and at least 50% of the produced heat can be sold if the SRC is processed by flash pyrolysis. If the SRC is gasified, all heat needs to be sold in order to render the *NPV* of cash flows positive. The most profitable situation however is attained by the investment in a pyrolysis plant for CHP production. It is also the only choice that guarantees a 100% chance of a positive *NPV*.

At an electrical capacity of 10 MW it is still not profitable to invest in gasification for electricity production. CHP production however is both profitable by means of gasifying or flash pyrolyzing the short rotation coppice, already when 25% of the heat can be sold. Flash pyrolysis followed by CHP however, still is the most profitable technology choice at an electrical capacity of 10 MW.

In the case of an electrical capacity of 20 MW, the most profitable situation appears to be attained by an investment in a gasification plant for CHP production. At an electrical capacity of 20 MW however, the choice for gasification is not clear if one takes into account uncertainties. Both flash pyrolysis and gasification for CHP production have a 100% chance of a positive *NPV*, but it is not clear which technology will result in the highest *NPV*. After all, the choice of the most profitable situation for an electrical capacity of 20 MW based on the *NPV* of the base model (gasification CHP plant) differs from the choice of the most profitable situation based on the mean value of the *NPV* (pyrolysis CHP plant). An ad hoc analysis of the most uncertain variables(e.g. investment parameters) is then required in order to be able to correctly estimate biomass conversion economics.

The variables that have the largest influence on the *NPV* of the investment project are the specific coefficient *b* of a certain component of the total investment costs and the electrical efficiency of the project. Lower values of such *b* coefficients, representing stronger economies of scale, have a large positive influence on the level of the *NPV*. These variables together explain at least 90% of the variance in *NPV*. Investment cost estimation and the energetical performance are thus key variables in future economic research.

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